

## **Combining Acoustic, In-Situ, and Remotely-Sensed Data with Regional Ocean Models in the East China and Philippine Seas**

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### **LONG-TERM GOALS**

The long-term scientific objective of the Quantifying, Predicting, and Exploiting (QPE) Uncertainty Directed Research Initiative (DRI) is to improve the assessment of uncertainty in observations and predictions of sound propagation in littoral regions.

### **OBJECTIVES**

The goal of this research is to understand and exploit the effects of the ocean state on acoustic propagation and detection. This work will contribute to that goal through regional ocean modeling and data assimilation. The modeling will include forecast and predictability studies to see the growth of uncertainty in time and space and the predictability of the propagation conditions on the shelf north of Taiwan from the ocean state.

### **APPROACH**

The QPE DRI is a coordinated effort in which many types of measurements have been collected over the continental shelf to the north of Taiwan. The field results will be used to help characterize the rapidly varying physical environment and to study acoustic propagation and scattering in the region.

The technical approach centers on using the Frechet derivative (adjoint) of a regional ocean model to explore the sensitivity of critical environmental features of the shelf region to the ocean in the region, to forcing, and to boundary conditions. In the longer term, acoustic remote sensing data,

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together with data from direct measurements and satellite remote sensing, will be assimilated into a regional ocean model to estimate the evolving ocean state using the adjoint technique.

Initially we configured a fine-resolution ( $1/12^\circ$ ) regional general circulation ocean model, using the MIT general circulation model (MITgcm), for a region encompassing Taiwan. This model can provide lateral boundary conditions to a smaller regional model to the northeast of Taiwan being run by Lermusiaux (MIT). Initial and lateral boundary conditions for our model are obtained from a global  $1/12^\circ$  Hybrid Coordinate Ocean Model (HYCOM) assimilation product. The choice of lateral boundary conditions is central to the issue of uncertainty. HYCOM is forced with daily Navy Operational Global Atmospheric Prediction System (NOGAPS) fluxes and uses the Navy Coupled Ocean Data Assimilation (NCODA) to assimilate data. First we needed to determine the fidelity of the output in the larger northwest Pacific region by considering the representation of those processes that will be felt at the boundaries of our regional model. These are primarily westward propagating mesoscale eddies. We also needed to consider the variability of the surrounding waters such as the annual cycle, mean flows, stratification and mixed layer depths.

In preparation for the regional modeling/data assimilative effort we gathered both in-situ and remotely sensed data for the larger northwest Pacific region. These data include temperature and salinity vertical profiles from Argo floats, Expendable Bathythermograph (XBT) temperature data, velocity and temperature at 15 m from surface drifting buoys, sea surface height from altimetry, and sea surface temperatures. The data was quality controlled and manipulated as appropriate for insertion in the data assimilation scheme.

Once the regional model and data assimilation machinery was working, sensitivity studies were conducted prior to the FY09 experiment to aid in the design of the experiment and to understand the sensitivity of the models to the various data types and geometries. The intent is to be ready to combine the data obtained during the FY09 experiment with realistic ocean models when the observations become available in order to provide accurate estimates of the ocean state.

## **WORK COMPLETED**

In the past year, the project focus has turned from evaluation of existing global model output to regional modeling of the Taiwan region. Two sets of regional MITgcm runs have been conducted, one in a large region that extends from  $116^\circ\text{E}$  to  $140^\circ\text{E}$  and from  $17^\circ\text{N}$  to  $27^\circ\text{N}$ , and the other in a domain one quarter the size, which extends from  $116^\circ\text{E}$  to  $128.5^\circ\text{E}$  and from  $22^\circ\text{N}$  to  $27^\circ\text{N}$ . The larger domain has been run at  $1/12^\circ$  and  $1/24^\circ$  degree, while the small domain has been run at  $1/24^\circ$  degree. Both setups used 50 layers in the vertical, including 5m spacing near the surface.

The simulations were evaluated based on the realism of environmental features seen as keys for the observational program. The Kuroshio path was compared to float observations by Centurioni and Niiler, including both the Luzon Strait Loop Current and the Kuroshio surface water intrusions onto the shelf northwest of Taiwan. The similarity of the "Cold Dome" feature in the model to historical observations was also examined.

The simulations in the large domain were run with a variety of initial conditions, boundary conditions, and forcing, in order to evaluate the model skill and its sensitivity to the controlling inputs ("controls"). Simulation periods of one to five years were tried, depending on the forcing product availability.

Initial and boundary conditions from both  $1^\circ$  ECCO and  $1/12^\circ$  HYCOM were used, and the higher-resolution HYCOM boundary conditions seemed to produce a better Kuroshio behavior north of Taiwan. A number of forcing fields were tried, including the NCEP/NCAR Reanalysis, NOGAPS, QSCAT winds, a combination of NCEP fluxes and NOGAPS winds, and similar combinations of NCEP or NOGAPS fluxes with QSCAT winds. No forcing product was clearly superior, but the NCEP fluxes with QSCAT winds seemed to have good performance.

Three topography estimates were tried: ETOPO2, HYCOM bathymetry, and NCOR bathymetry supplied by the Taiwanese collaborators. The NCOR bathymetry had the most realism in the key experimental region NW of Taiwan, but the HYCOM topography gave the best Kuroshio behavior across the Luzon Strait. Simulations with NCOR topography showed several large intrusions of the Kuroshio into the Luzon strait, not consistent with observations, also calling into question the behavior of the Kuroshio along the east coast of Taiwan after exiting the Luzon strait. Experiments with doubled resolution and a variety of perturbed boundary conditions (in addition to the forcing products) did not change these results. Although some sensitivity analyses were carried out in the larger domain, the results were subject to concerns about model resolution and Kuroshio path.

The smaller domain runs were adopted to focus more on the experimental region, and to eliminate the issue of the Luzon Strait Loop Current. The smaller domain allowed doubled horizontal resolution, also a key component of realism in the interaction with topography. To take advantage of recent data, the simulations were run for recent years: 2004 through 2008. Both NOGAPS and QSCAT winds were used with NCEP fluxes, and both wind products showed reasonable features.

The forward runs showed realistic Kuroshio position, including intrusions onto the shelf, and had generally good cold dome structure. Cold features were formed both by interaction of the Kuroshio with the topography and by strong wind forcing on the shelf. The cold features were also influenced by the Taiwan Strait flow and its seasonal variability. The cold dome timescale was seen to be approximately ten days. The upwelling of high-salinity Kuroshio water was seen in the center of the cyclonic eddy forming the cold dome in some cases.

Several typical events were chosen for sensitivity analysis, running the adjoint model backward in time from the location and time of a cold dome or intrusion event. The sensitivity maps showed upstream dependence of the cold dome and intrusions in line with expectations, and showing both growth and decay of sensitivity with time lag, depending on location. These results were delivered to the Chief Scientist for use in planning the experiment.

The secondary focus of the project this past year has been the continued analyses of the  $1/12^\circ$  HYCOM data assimilative and forward simulations in the northwestern Pacific and preparation of results for publication. The entire duration of both simulations have been analyzed in terms of the predictability of intrusions of the Kuroshio into the East China Sea and the regional circulation near Taiwan. Specifically we have examined how the remote oceanic signal in the form of westward propagating mesoscale eddies interacts with the Kuroshio causing it to often first meander offshore and then intrude over the shelf north of Taiwan. These results complement the downscaled findings obtained from the regional models that use HYCOM output as lateral forcing.

## **RESULTS**

The adjoint model has worked successfully to show the sensitivity of key environmental features on the upstream ocean state, information used for the design of the observational programs. The sensitivities will allow a rapid propagation of uncertainties forward in time to regions of interest.

## **IMPACT/APPLICATIONS**

This study will lead to the improvement of the assessment of uncertainty in observations and predictions of sound propagation in littoral regions.

## **TRANSITIONS**

Methodology and data results can be made available to Navy scientists.

## **RELATED PROJECTS**

The work described here is in collaboration with Professor Peter Niiler at SIO and Dr. Pierre Lermusiaux at MIT.